Simple design for 3-D reconstruction of ~MeV energy deposits in dense scintillator

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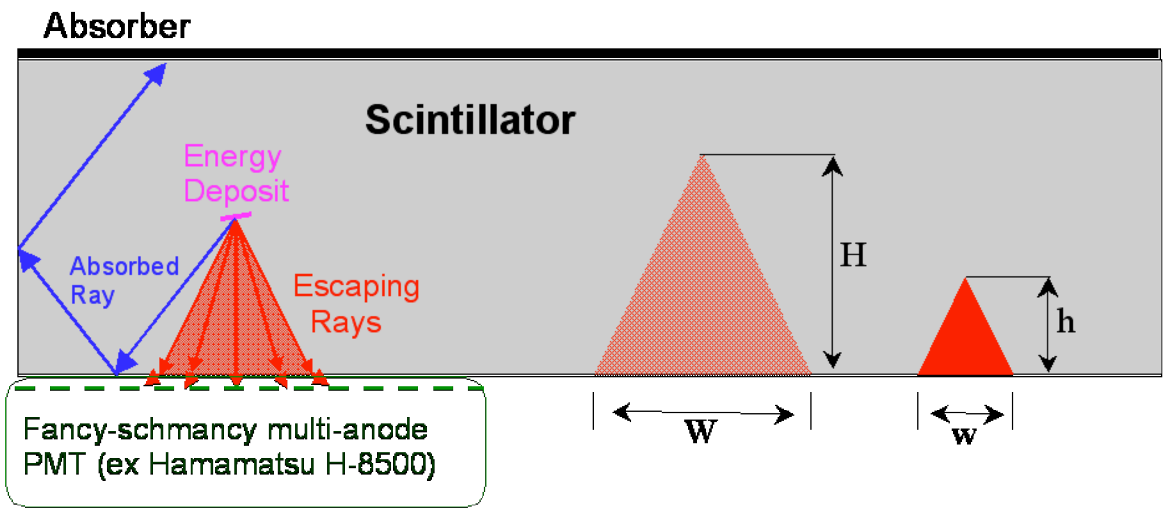
Suppose a gamma ray of ~MeV energy interacts in a dense scintillator. The scattered electron then deposits its energy over a very short track, on the order of millimeters. We should be able to reconstruct the full 3-D position of the electron track, to an accuracy on the order of millimeters in all three dimensions, by detecting the "first light" photons emerging from the site of the deposit and traveling to one side of the scintillator block without reflection. The basic idea is illustrated here:



Assume we attach some kind of phototube or photodiode array to one side of the scintillator block. Assuming the scintillator has a higher optical index than the optical coupling attached to it (which is typically the case) the only photons which can escape through that side are those with angles close to the normal (red rays), since the rest are trapped inside the block through total internal reflection (blue rays). If we then cover the opposite side of the block with some kind of photon absorber, we can see that all photons with initial directions outside the critical cone will be eventually be absorbed. At the same time, all the photons which leave the block will do so without reflection, so the detector array will see purely "first light" inside one critical cone from the location of the energy deposit.

(The picture clearly changes -- slightly -- if the deposit is near the edge of the block. For the moment we will assume that the scintillator block is a big slab, and worry about effects at the edges separately.)

The first-light rays will emerge from the scintillator and hit the detector over a "patch" whose size is on the order of the depth into the block at which the deposit took place, *ie* similar to the thickness of the block. If the detector is chosen to be thick enough to have a high chance of gamma-ray absorption, then this will probably be on the order of a few centimeters or more. If the detector array has elements of smaller size – say, a few mm up to 5 mm – then we should be able to reconstruct the position and size of the patch of photons in the plane of the side of the block as they exit. There are at least two different kinds of detectors currently available which could serve here: (i) photodiode arrays, and (ii) multi-anode phototubes (see for example the Hamamatsu H-8500 PMT, as suggested in the figure, which has an 8x8 array of detectors each of size $(6\text{mm})^2$).

The centroid of this patch in that plane will clearly track the 2-D position of the energy deposit within a parallel plane. This technique has already been proposed for 2-D reconstruction within thin scintillator slabs, as an alternative to finely-segmented arrays of individual mm-sized scintillator blocks. Those designs typically do not use an absorber as shown here, but instead reflect the non-direct light back to the detector in order to increase the total number of detected photons while leaving the centroid of the patch unchanged.

What's more interesting is to note that if we do restrict ourselves to receiving only the direct-exiting first light onto the detector array, then the width of the detected patch will be directly proportional to the depth within the block at which the energy deposit took place. This should be clear from the right side of the figure: since the critical angle for escape is always the same, the width W varies directly with the depth H. The width of the patch can be measured in either transverse direction, or both for better accuracy.

So by observing the patch in a segmented detector with small enough elements, we can reconstruct the full 3-D position of the original interaction: the centroid of the patch gives us the 2-D position parallel to the plane of the side of the scintillator, and the width of the patch gives us the depth away from that plane. What accuracy might we expect for each of these? As long as the detector elements are small compared to the size of the patch, the limiting factor on the position accuracy will be the number of detected photo-electrons (PE). Generically speaking, if σ is the spatial width (ie standard deviation) of the PE distribution in the detectors, and σ is large compared to the detector segmentation, then we can expect the accuracy on reconstructing both the mean and the width of the distribution to be on the order of:

resolution ~= σ/sqrt(number of PE)

The width σ will be on the order of the depth into the block, or a little smaller; this will probably be a few centimeters with a fairly thick scintillator (*ie* one or two interaction lengths). For any good, high-light-yield scintillator a deposit of, say, 0.5 MeV energy will create 10,000-20,000 photons; once we account for geometric collection efficiency and photocathode quantum efficiency, we should still have on the order of several hundred PE's detected per event. So the very rough estimate of the spatial resolution is that it should be on the order of millimeters, in all three directions. Personally my guess is that 5mm would be easy to achieve, 2mm is possible, 1mm would probably test the technique to the limit. But it should be quite easy to get a realistic answer even with a fairly quick, simple simulation.

A simple improvement is possible if we can afford to instrument both sides of the scintillator slab, and so catch two patches of photons in two critical cones. This will improve the spatial resolutions simply by doubling the number of photo-electrons; and also because the patch widths on the two sides will vary oppositely with the depth of the interaction, which could in principle provide a better constraint on measuring that depth. This latter point could be especially important when the energy deposition is very close to one side or the other of the scintillator block.

Of course, we will see fewer PE's by using only the "first light" photons in a single critical cone, so we should not expect a great energy resolution with this detector. It is perhaps better to think of this design as a method of swapping energy resolution for spatial resolution. However, it is useful to note that the angle of the critical cone, and so the number of detected photons, is basically independent of the depth at which the interaction takes place (assuming the scintillator has little absorption over centimeter path lengths).